

***DHWcalc*: PROGRAM TO GENERATE DOMESTIC HOT WATER PROFILES WITH STATISTICAL MEANS FOR USER DEFINED CONDITIONS**

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ABSTRACT

A program to generate **Domestic Hot Water** (DHW) profiles has been developed. The generated profiles are text-files, containing a list of flow rate values for each time step. They are used primarily for annual system simulations, but are also suitable to be used for test procedures of laboratory system or component tests.

The program distributes DHW draw-offs throughout the year with statistical means, according to a probability function. Reference conditions for the draw-offs (flow rates, draw-off periods, etc.) and reference conditions for the probability function (daily probabilities for draw-offs etc.), can be set by the user, as well as general profile parameters like time step period and mean daily draw-off volume.

The program can be downloaded free of charge at the web page: www.solar.uni-kassel.de.

1. INTRODUCTION

Up to date a large variety of different DHW profiles for simulations of solar heating systems as well as for test sequences have been used by solar energy research institutes. Most of the profiles used were rather simple, with long draw-off periods and constant flow rates. For example, only three daily hot water draw-offs with a constant flow-rate of 10 l/min were used for system simulations and test procedures for solar heating systems in German and European standards (DIN 4708, EN 12977), while various national testing institutes all over Europe used different numbers of daily hot water draw offs, mostly with one defined flow rate. The impact of the DHW profiles on the system performance of a solar heating system has been shown, for example in (Shariah and Löf, 1997; Frei et

al., 2000; Jordan, 2001; Knudsen 2001; Bales et al., 2004).

The program *DHWcalc* is based on a code used for IEA-SHC Task 26 on solar combisystems (Weiss 2003, and Jordan and Vajen, 2000). The code was developed in order to be able to compare solar combisystems from different European countries with fairly realistic reference conditions for the domestic hot water consumption. The reference conditions agreed on in the IEA task are implemented in the program as default values for certain parameter configurations.

As described in (Jordan and Vajen, 2000) general assumptions have been extracted from several studies carried out about domestic hot water consumption (Dittrich et al., 1972; Loose, 1991; Dichter, 1999; Nipkow, 1999; Real et al., 1999). For example, according to (Mack et al., 1998) the seasonal distribution of the hot water consumption is described as a sine function over the year. The amplitude and shift of the sine function are parameters to be defined by the user in the program interface of *DHWcalc*.

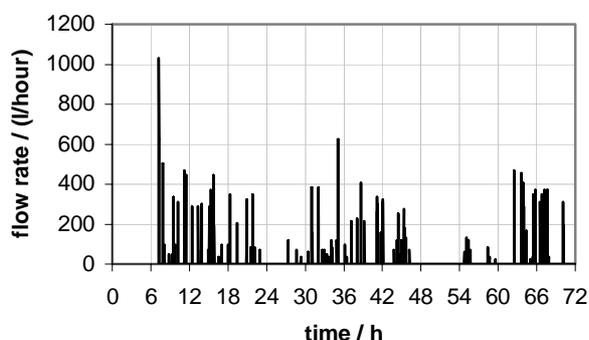


Fig. 1: Example of a DHW-profile for a single-family house. Time step: 1 min.

An example of a three day-period of a DHW-profile for a single-family house is shown in Fig. 1. For single-family houses, most values of the text-file equal to zero, with only few non-zero flow rate-values in between, distributed over the total duration.

In the following paragraph the user interface of the program is described. The user defined parameters are listed and their implementation in the code is described briefly. Section 3 deals with the statistical method to distribute the draw-offs over the period of the profile. Finally, the contents of the output files and an example of the distribution of daily hot water consumption for typical reference conditions are given in section 4 and 5, respectively.

2. USER INTERFACE

Parameter settings of three kinds may be defined by the user:

- 1.) General profile parameters,
- 2.) parameters concerning the draw-offs, and
- 3.) parameters concerning the statistical distribution of the draw-offs during the defined period of the profile.

2.1 General Parameters

The following general profile parameters can be defined and general options can be chosen:

- Single or Multi Family House (important regarding holiday periods)
- Number of draw-off categories (bath, shower, etc.) for flow rates
- Time step period in minutes (draw-off periods are multiple integers of the time step period)
- Start day of the profile
- Total profile period in days
- Total mean daily draw-off volume in litres/day

The main window of the user interface is shown in Fig. 2.

2.2 Probability Distributions

The number of draw-off incidences is calculated by the total annual draw-off volume (of each category) divided by the mean flow rate for each category. In order to spread the draw-off incidences throughout the time period for the profile, the cumulated frequency method was applied. This method is based on the integral function of a probability function. It is described in section 3.

The probability function of draw-offs is described by the product of probability functions for seasonal, daily, and week-daily variations of DHW-consumption.

The user interface to set parameters of probability distributions is shown in Fig. 3.

2.2.1 Probability During the Day

One out of three options can be chosen for probability distributions during the day:

- a) Default distributions, described as Gaussian and constant curves for the draw-off categories: Small and medium flow rates, showers and baths.
- b) Step functions, with up to 6 steps during the day, different for weekdays and weekend-days.
- c) Step functions with a minimum time interval of one hour, same for each day.

a) Default Distributions

A pre-defined probability distribution is based on Gaussian and step functions as shown in Fig. 4a. Four categories of loads are defined. For two categories (small and medium draw-offs) a constant probability

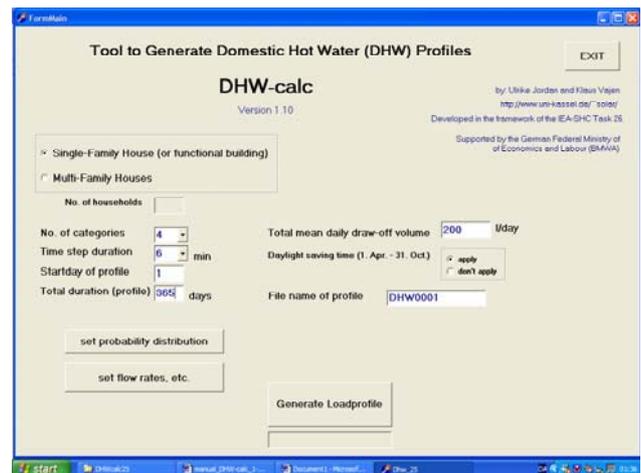


Fig. 2: Main window of the user interface.

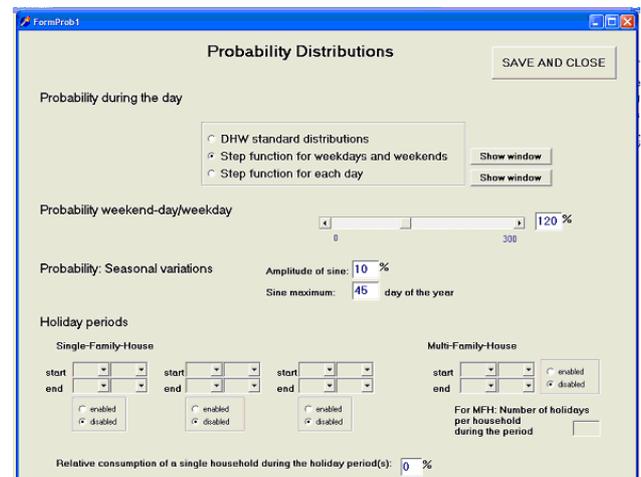


Fig. 3: Window to fill in parameters to define probability distributions.

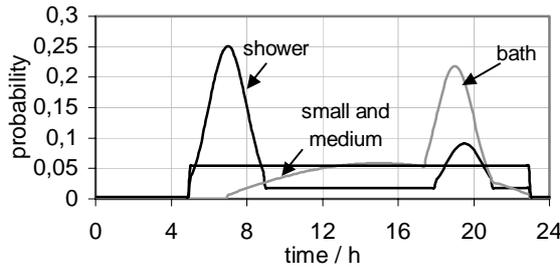


Fig. 4a: Probability distribution load in the course of the day. Category 1 and 2: For small and medium draw-offs the probability is distributed equally between 5:00 and 23:00 h. Category 3: Bath, Category 3: Shower.

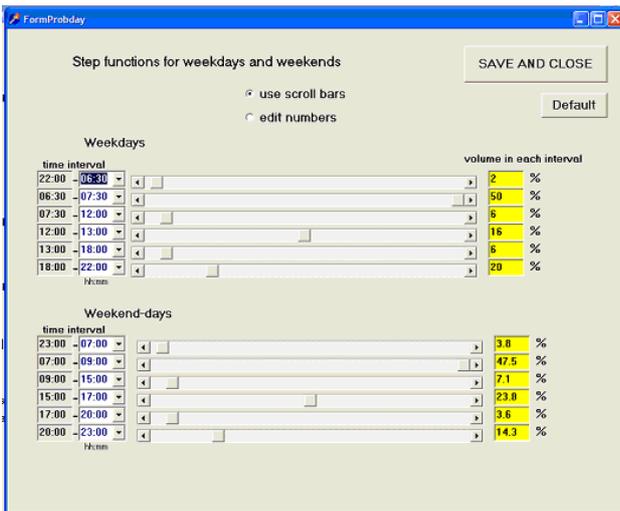


Fig. 4b: Window to define the daily probability distributions as two different step functions, one for weekdays, the other one for weekend-days, for up to 6 time intervals for weekdays as well as for weekend-days.

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
00:00	0	0	0	0	0	0	0
01:00	0	0	0	0	0	0	0
02:00	0	0	0	0	0	0	0
03:00	0	0	0	0	0	0	0
04:00	4.36	4.36	4.36	4.36	4.36	8.72	8.72
05:00	26.17	26.17	26.17	26.17	26.17	39.25	39.25
06:00	43.61	43.61	43.61	43.61	43.61	65.42	65.42
07:00	26.17	26.17	26.17	26.17	26.17	39.25	39.25
08:00	4.36	4.36	4.36	4.36	4.36	4.36	4.36
09:00	4.36	4.36	4.36	4.36	4.36	4.36	4.36
10:00	4.36	4.36	4.36	4.36	4.36	4.36	4.36
11:00	4.36	4.36	4.36	4.36	4.36	4.36	4.36
12:00	4.36	4.36	4.36	4.36	4.36	4.36	4.36
13:00	4.36	4.36	4.36	4.36	4.36	4.36	4.36
14:00	4.36	4.36	4.36	4.36	4.36	4.36	4.36
15:00	4.36	4.36	4.36	4.36	4.36	4.36	4.36
16:00	4.36	4.36	4.36	4.36	4.36	4.36	4.36
17:00	4.36	4.36	4.36	4.36	4.36	8.72	8.72
18:00	13.08	13.08	13.08	13.08	13.08	21.81	21.81
19:00	13.08	13.08	13.08	13.08	13.08	21.81	21.81
20:00	4.36	4.36	4.36	4.36	4.36	4.36	4.36
21:00	4.36	4.36	4.36	4.36	4.36	4.36	4.36
22:00	0	0	0	0	0	0	0
23:00	0	0	0	0	0	0	0
Sum	178.79	178.79	178.79	178.79	178.79	252.94	252.94

Fig. 4c: Window to define the daily probability distributions as a different step function for each day of the week with a step size of 1 hour.

for draw-offs is assumed during daytime and nighttime, respectively. For the other two categories (shower and bath) Gaussian distributions with peaks in the morning and evening, respectively, are defined to describe the probabilities during the day. Each category-profile is generated separately and superposed afterwards.

b) Step Functions for Weekdays and Weekend-Days

Two daily probability step functions can be defined with this option, one for weekdays and one for weekend-days (Fig. 4b). Therefore the probability for a draw-off at a certain time of each day is equal from Monday to Friday, and it is equal on Saturdays and Sundays. Up to six daily intervals can be defined for each of these periods.

The values in the (yellow) boxes on the right side of the window (p_{step}) show the part of the mean daily draw-off volume for each time interval in percent of the total mean daily draw-off volume. The values in the boxes increase, when either the corresponding time interval is enlarged or the scroll bar next to the box is moved to the right.

p_{step} are calculated with:

$$p_{step}^i = \frac{\Delta t_{step}^i \cdot pos^i}{\sum_{j=1}^6 (\Delta t_{step}^j \cdot pos^j)} \quad (\text{eq.1})$$

with

$i, j = 1..6$ (no. of time interval)

pos^i : scroll bar position of the six time steps i with values between 0 and 100, $pos^i \in [0,100]$

Δt_{step}^i : time intervals, between the times shown in the white and corresponding grey boxes.

c) Step Functions for Each Day

The third option provides the possibility to apply special consumption patterns, which differ much for the different days of the week, e.g. for sport halls or hospitals (Fig. 4c).

A mean draw-off volume (in litres) can be set for each hour of the week.

The values will be normalized, to reach the right value for the total draw-off volume.

2.2.2 Probability Weekend-Day/Weekday

The proportion of mean draw-off volume on weekend-days compared to weekdays is set with the slide bar **Probability Weekend-day/Weekday** in the *Probability Distribution Window* (Fig. 3). For example, if it is set to 1.2, $p_{weekend}(t)$ is set to:

$$p_{weekend}(t) = \begin{cases} 0.945 & \text{for } t \in \text{weekday} \\ 1.14 & \text{for } t \in \text{weekend} \end{cases}$$

2.2.3 Probability: Seasonal Variations

Seasonal variations are described by a sine function with a period of 365 days. The amplitude of the sine function and the day of the year at which the sine maximum occurs can be set.

2.2.4 Holiday Periods

For single-family houses up to three periods can be defined. During these periods the DHW consumption is usually reduced to zero. If a non-zero, but reduced DHW consumption should be taken into account during these periods, the reduced portion (percentage of the regular probability for draw-offs at that day) needs to be set in the edit-box situated at the bottom of the window.

For multi-family houses a long period (of usually a few months) marks the whole period within which holidays are taken into account for individual households of the house. The holiday duration for each household can be specified in the edit-box next to the start- and end- date buttons. The start date for each single holiday duration is generated with the random generator.

2.3 Parameters of the Draw-Offs

The following parameters concerning the statistical distribution of the draw-offs can be defined in the *Flow-Window*, shown in Fig. 5:

- *Mean flow rate*: Peaks of the Gaussian curves, shown in Fig. 6.
- *Draw-off duration*: Must be a multiple integer of the profile time step.
- *Standard deviations of the Gaussian functions*: Determines the width of the Gaussian curves.
- *Minimum flow rate*
- *Maximum flow rate*: For multi-family houses, the total maximum flow-rate (limit for the superposition of draw-offs in different households and of different categories)
- *Portion*: Percentage of volume assigned to each category.

(If only one category is chosen, a simplified *Flow-Window* opens.)

For each category a mean flow rate is defined. The values of the flow rates for the profile are spread around the mean value with a Gaussian-distribution:

$$\text{prob}(\dot{V}) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(\dot{V} - \dot{V}_{\text{mean}})^2}{2\sigma^2}\right) \quad (\text{eq.2})$$

A flow rate step size of 0.1 l/min = 6 l/h is defined by the program.

The minimum and maximum flow rates for each category are determined by adding and subtracting twice the standard deviation σ from the mean value set in the first row in Fig. 5, unless the total minimum or maximum flow rates (also set in the *Flow Window*) are exceeded.

$$\dot{V}_{\text{min}} = \dot{V}_{\text{mean}} - 2 \cdot \sigma \quad \text{and} \quad \dot{V}_{\text{max}} = \dot{V}_{\text{mean}} + 2 \cdot \sigma$$

In Fig. 6 the flow rate distributions are shown which are applied if the option '*DHW standard distribution*' is chosen. The curves show Gaussian flow rate distributions for four categories. The categories represent small and medium draw-offs, shower, and bath. In the figure, the total duration of draw offs during a year is shown as a function of the flow rate.

	Cat. 1	Cat. 2	Cat. 3	Cat. 4	
mean flow rate per draw-off	30	360	720	480	l/h
draw-off duration	1	1	10	5	min
portion	14	36	10	40	%
standard deviation	120	120	12	24	l/h
mean volume per draw-off	1	6	120	40	l
mean no. of draw-offs per day	28	12	0.166	2	
mean draw-off volume per day	28	72	20	80	l

min. flow rate: 1 l/h
max. flow rate: 1200 l/h (after superposition)
mean daily draw-off volume: 200 l/day

Fig. 5: *Flow Window* to specify flow rates, draw-off durations and the standard deviation of the Gaussian distribution of flow rates for up to 4 draw-off categories.

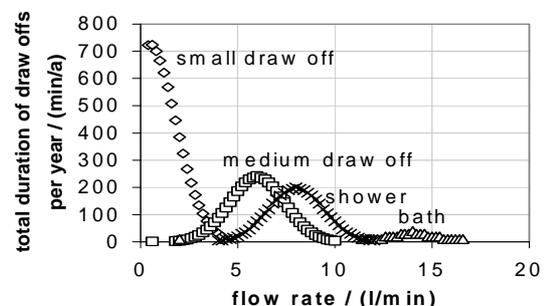


Fig. 6: Example for flow rate distributions for four categories.

3. CUMULATED FREQUENCY METHOD

The transient probability function $p(t)$ is calculated as the product of daily (p_{day}), weekly (p_{weekday}), seasonal (p_{season}) probability distributions and the holiday step functions (p_{holiday}) for every time step:

$$p(t) = p_{\text{day}}(t) \cdot p_{\text{weekday}}(t) \cdot p_{\text{season}}(t) \cdot p_{\text{holiday}}(t)$$

Parameters of the probability distributions are set in the *Probability-Distribution-Window* (Fig. 3).

- $p_{\text{day}}(t)$ is described as superposition of Gaussian functions or step functions,
- $p_{\text{weekday}}(t)$ is described as a step function to take into account different mean draw-off volumes on weekdays compared to weekend-days,
- $p_{\text{season}}(t)$ is described as a sine function, and
- $p_{\text{holiday}}(t)$ is described as a step function for reduced number of draw-offs during holidays.

The integral $I(t)$ over the probability function $p(t)$ from the start time t_{min} to the time t is then normalized:

$$I(t) = \int_{t_{\text{min}}}^t p(t) dt$$

For each draw-off a random value with $\text{ran} \in [0,1[$ is generated.

The time step t in which each draw-off occurs, is then given by the dependent variable of the integral function: $\text{ran} = I(t)$ (see Fig. 7).

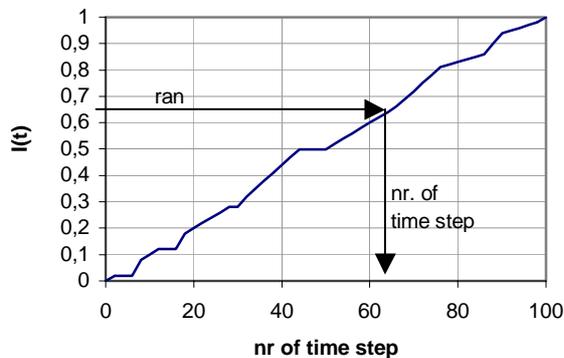


Fig. 7: Cumulated frequency method: Random values for each draw-off are distributed over the time period according to the probability integral function $I(t)$.

4. OUTPUT FILES

Four output files are delivered, containing

- a value for a DHW flow rate in litre/hour for each time step in the duration chosen,
- a listing of the draw-offs: flow rates (in litres/hour) and the number of time step, in which each flow is drawn,

- sums of DHW draw-off volumes during each day, and sums of the DHW draw-off volumes for each hour of the year for the total period,
- information about all input data supplied by the user (log-file).

For example, an annual profile with a time step of 6 minutes contains 87 600 lines with one integer value each.

5. EXAMPLE OF DAILY DRAW-OFF VOLUMES

In Fig. 8 the daily draw-off volume in the course of the year is shown for an example DHW profile generated with *DHWcalc*, with a mean value of 2000 l/day (e.g. for a ten-family house). The sine function, used to calculate the probability p_{season} with an amplitude of 200 l/day (10% of the mean daily draw-off volume) is shown with a solid line. Two holidays weeks are distributed by random values between June 1st and Sept. 30th for each household.

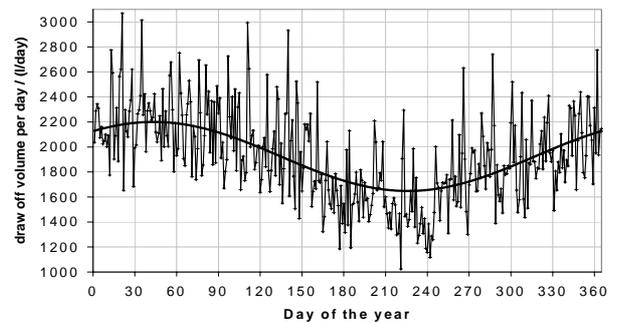


Fig. 8: Daily draw-off volume in the course of the year for a ten-family house, calculated from a DHW profile generated with *DHWcalc*.

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